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Enhancing K-14 Education through the Study of Additive Manufactured Bioinspired Lattice Structures

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Mechanical Performance of Additive Manufactured Bioinspired Lattice Structures

Abstract

This summary report presents the outcomes and advancements in the field of Fused Filament Fabrication (FFF) for the printing of bioinspired lattice components. The National Science Foundation (NSF) has been a pivotal supporter of research in this domain, and this report aims to highlight the key developments, challenges, and prospects in this exciting area of scientific exploration. In this study, the mechanical properties of bio-inspired lattice structures produced through FFF-based 3D printing have been investigated. The samples consist of two different polymers namely, polylactic acid (PLA) and thermoplastic polyurethane (TPU) with distinctly different mechanical properties. The present study considers a triply periodic minimal surfaces (TPMS) lattice structure to investigate the effect of processing conditions effects on the mechanical properties. Standardized tensile testing is performed to evaluate the mechanical properties of the printed components. The results highlight the effect of processing conditions on the mechanical properties of the TPMS composites as well as its potential advantages and suitability for applications in various industries.

1.0 Introduction

Nature's design solutions, honed over billions of years of evolution, have given rise to a myriad of remarkable features such as hierarchical structures, lightweight composites, self-healing mechanisms, and optimal geometries [1-3]. These features not only ensure exceptional mechanical properties to living organisms but also ensure energy efficiency and resilience in the face of environmental challenges [4-8]. The integration of such principles into 3D-printed objects holds the potential to revolutionize fields ranging from aerospace to consumer goods. Lightweight structural design refers to the process of developing structures that are optimized to achieve significant weight reduction without compromising their mechanical performance or integrity. The aim is to create structures that utilize materials and geometries in a way that minimizes weight while maintaining or enhancing strength, stiffness, and functionality [9-12]. Lightweight structure design and optimization offer several benefits. First and foremost, weight reduction leads to improved fuel efficiency, energy savings, and reduced environmental impact [13]. It also allows for increased payload capacity, extended range, and improved maneuverability in transportation and aerospace applications [14-16]. Additionally, lightweight structures can offer better resilience to dynamic loading, enhanced vibration damping, and improved thermal management [17-21]. Lightweight structure design and optimization also contribute to cost savings by reducing material usage and transportation costs. Thus, the motivation behind lightweight structure design and optimization stems from the desire to address various challenges faced by industries, including transportation, aerospace, construction, and energy. These challenges include the need for fuel efficiency, reduced emissions, increased payload capacity, improved structural integrity, and enhanced sustainability. By reducing the weight of structures, these goals can be achieved while maintaining or improving performance and functionality.

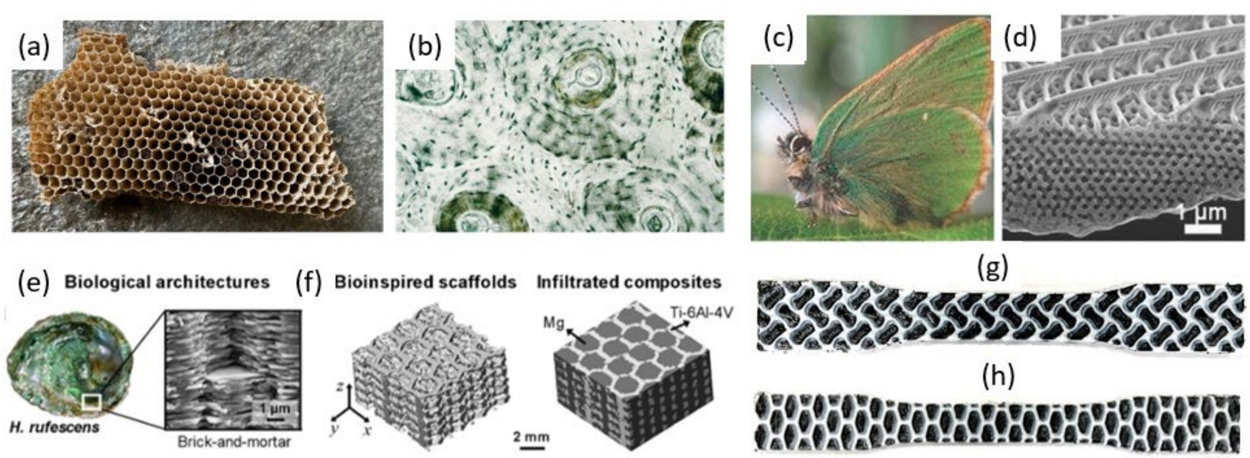

Figure. 1. Nature-inspired Design.

The integration of bio-inspired design into 3D printing opens up new avenues in various fields. In aerospace, lightweight and strong structures inspired by the wing structures of birds could lead to improved fuel efficiency and reduced emissions. Healthcare applications could benefit from 3D-printed implants that replicate the porous structure of bone, enhancing integration and healing. In architecture, it enables the creation of buildings that are not only aesthetically pleasing but also energy-efficient, drawing inspiration from the adaptive and efficient features of natural structures like honeycombs and tree branches.

Fused Filament Fabrication (FFF), a subset of additive manufacturing, has gained considerable attention for its potential applications in creating bioinspired lattice components. These lattice structures mimic nature's design principles, offering enhanced mechanical properties, lightweighting, and multifunctional capabilities. The present study incorporates polylactic acid (PLA) and thermoplastic polyurethane (TPU) to print the TPMS structure. Thermoplastic polyurethane (TPU) filament is a common filament used in fused filament fabrication (FFF). It offers flexibility and resistance to various forces including abrasive and impact and is resistant to many common chemicals and oils. It is commonly used to create flexible and durable parts such as phone cases, soles of shoes, gaskets, and prosthetic parts. Polylactic acid (PLA) filament is also a common filament used in FFF. It is ideal due to its ease of printing good layer adhesion and minimal warping. It has low toxicity making it suitable for use in an educational setting. It offers strength and stiffness to the sample being printed. It is also commonly used for rapid prototyping due to its low cost and ease of printing. Moreover, It is used in the production of biodegradable materials such as packaging materials and disposable cutlery.

The present study aims to combine the power of 3D printing with bio-inspired structural material design to develop innovative engineering solutions. By mimicking the intricate designs found in nature, we hypothesize that 3D printed materials can exhibit enhanced mechanical properties, structural efficiency, and multifunctionality, opening new avenues for advanced additive manufacturing. The objective of this project is to explore the mechanical properties of bio-inspired composite materials. The possible applications of these types of materials run the range of aerospace, automotive, architecture, and biomedical engineering just to list a few. By studying nature's designs we are looking to create composites based on PLA-TPU that exhibit improved mechanical properties, lighter weight properties, and superior resilience.

2.0 Methodology:

2.1 Design and 3D Printing: In this present study, bio-inspired TPMS structures as shown in Fig. 2a and 2b are designed and printed. The TPMS equations delineate 3D surfaces that can be regarded as the demarcation between empty space (Porous/hollow) and solid material. By identifying the U = 0, iso-surface of these equations, it is possible to generate matrix phase gyroid structures with numerous cell counts and volume proportions:

$$U = \left[\cos(k_x x)\sin(k_y y) + \cos(k_y y)\sin(k_z z) + \cos(k_z z)\sin(k_x x)\right]^2 - t^2 \qquad (2.1)$$

$$k_i = 2\pi \frac{n_i}{L_i} \ (where, i = x, y, z) \qquad (2.2)$$

Where, n_i represents the quantities of cell repetitions along the x, y, and z axes, while L_i denotes the size of the structure in those respective directions. The present study considers the solid structure or backbone of the TPMS composites made of PLA (Fig. 2g) and empty/void space is filled by TPU (Fig. 2f). By combining these two structures we achieve composite components made of PLA and TPU as shown in Fig. 2h. A FFF printer with dual-extruder equipped with a 0.4 mm nozzle is used to print TPMS composite structure. All test specimens are printed using the printing parameters listed in Table 1. These parameters are optimized to accommodate complex geometries and hierarchical designs. In Table 1, T_e, T_b, v, and h represent extrusion nozzle temperature, build plate or bed temperature, scanning speed, and layer thickness respectively.

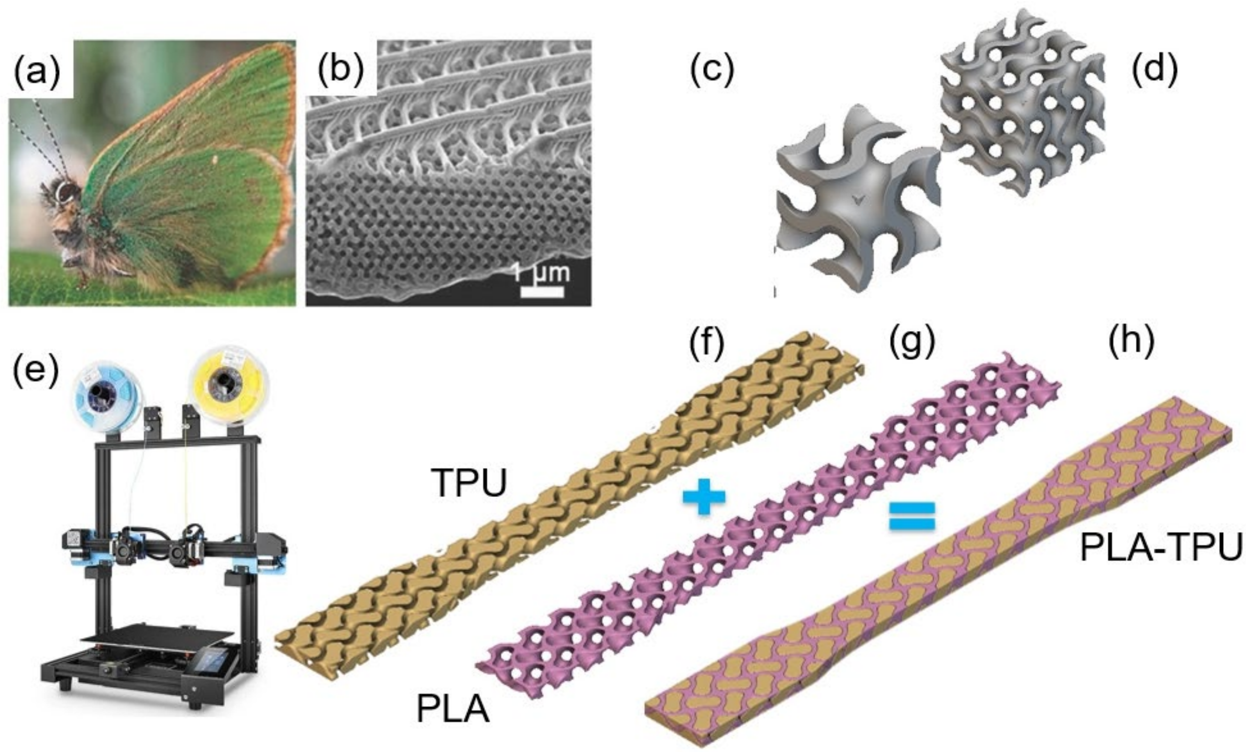

Figure. 2. (a) Butterfly wing structure [22], (b) computer model of butterfly wing inspired TPMS lattice structure, (c) Fused filament fabrication (FFF) tool, and (f)-(h) PLA-TPU TPMS composite structure.

Table. 1. Print Parameters used in this study for PLA and TPU polymers:

Filament	T_e (°C)	T_b (°C)	v (mm/s)	h (mm)	Infill (%)
PLA	210	60	40	0.3	100
TPU	230	60	20	0.3	100

2.2 Processing and Characterization:

After printing the TPMS samples, heat treatment was conducted at two different temperatures as illustrated in Fig. 3b. The specimens are categorized into four groups, each designated by a specific temperature (80 °C, and 120 °C) and duration of the heat treatment (1 hour and 2 hours). These temperatures were chosen based on the recrystallization temperature of the PLA and TPU. To achieve the desired temperature, a uniform heating rate was applied to all specimens, taking 15 minutes to reach the targeted temperature. Subsequently, the specimens were held at each of the two different temperatures for 1 and 2 hours. Following the prescribed temperature and time intervals, the specimens were allowed to cool naturally in the ambient air.

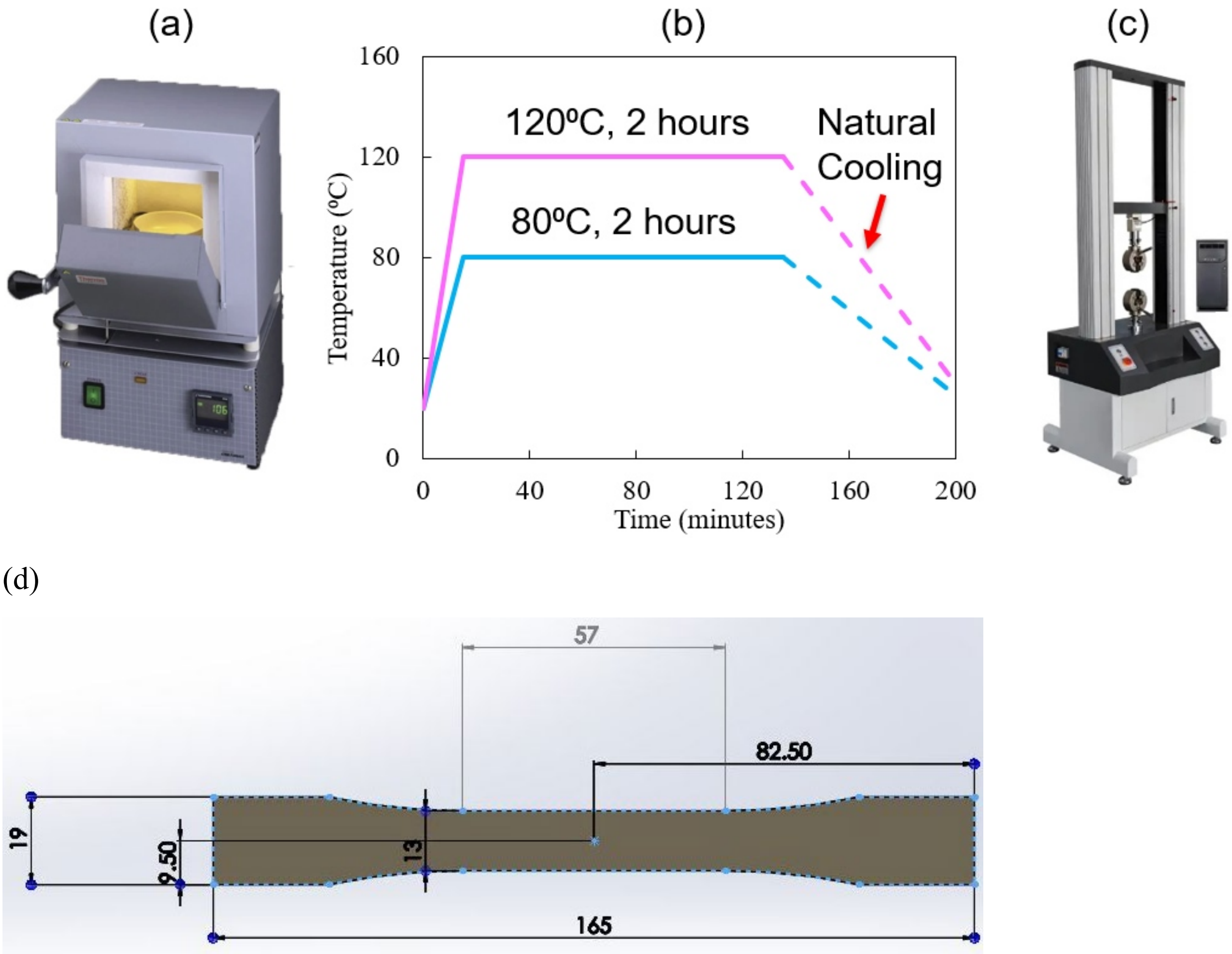

Figure. 3. (a) Schematic of a heat-treatment furnace, (b) heat treatment cycle, (c) mechanical testing set-up, and (d) Standard ASTM D638 Type I specimen (units are in millimeters).

The mechanical characteristics of all PLA-TPU TPMS structures were thoroughly evaluated under tensile loading condition with standard ASTM D638 Type I specimens as shown in Fig. 3d. All testing were performed using a Shimadzu 50kN Universal testing machine at room temperature with a crosshead travel speed of 5 mm/min.

3.0 Results and Discussion:

The results of the uniaxial tensile testing of the composite TPMS structure, both with and without heat treatment, provide valuable insights into the mechanical behavior of these printed components. These findings are summarized in Fig. 4a. As-printed sample (i.e., no heat treatment) displays a moderate level of ductility, as evidenced by the ability to deform without fracturing significantly. The ultimate failure strength (UTS) is found to be 11.3 MPa, indicating the maximum stress the material could withstand before failure, and the strain at failure is 8.8%, representing the extent to which the material could deform before breaking.

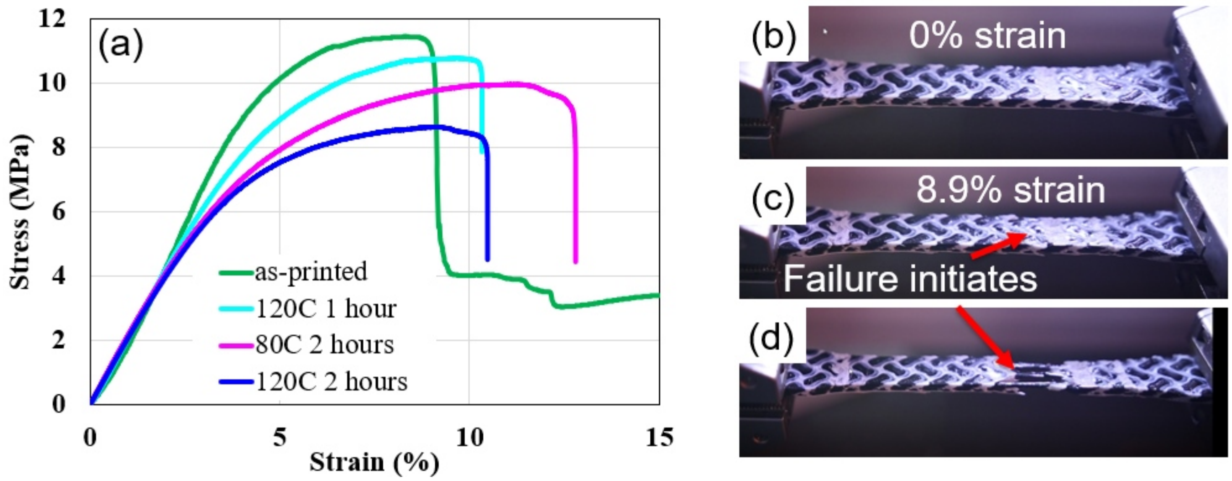

Figure. 4. (a) Tensile response of the samples, (b)-(d) Snapshot taken during the tensile testing.

The effect of heat treatment revealed that, regardless of the specific heat treatment conditions (temperature and duration), all heat-treated samples exhibited improved ductility. This means that the materials became more capable of deforming before breaking. However, this improvement in ductility came at the expense of strength, with the UTS decreasing as the heat treatment duration increased. An intriguing outcome is found with the sample subjected to 80°C heat treatment for 2 hours (illustrated in Fig. 4a). This particular heat-treatment condition achieved a unique balance between ductility and strength. It had a UTS of 9.9 MPa, showing that it is still quite strong, and a strain of 12.7%, indicating substantial ductility. Notably, this specific heat-treatment condition alone increased the failure strain by 44.3% compared to the as-printed sample. It also played a crucial role in enhancing fracture toughness. Interestingly, the analysis found that heat treatment duration had a limited effect on enhancing ductility, although it was associated with a significant reduction in UTS. This was evident in samples treated for varying durations at 120°C. The specific effects of heat treatment duration on mechanical performance warrant further investigation.

The study also explores the influence of TPU (Thermoplastic Polyurethane) infill in the void spaces of the TPMS structure. This had a significant effect on fracture behavior. Unlike the brittle fracture seen in pure PLA (Polylactic Acid) samples, all PLA-TPU TPMS structures exhibited enhanced ductility. This can be attributed to the continuous and substantial TPU region within the structure, which promoted a more flexible failure mechanism. Additionally, it is apparent in Fig. 4b-4d that even after the sample had failed, the continuous TPU region within the structure continued to elongate, suggesting a high degree of deformability and pliability.

The results highlight the potential for enhancing the mechanical properties of TPMS structures through controlled heat treatment and the incorporation of TPU infill. These findings offer promising avenues for further research and development. Ongoing studies aim to provide a more comprehensive understanding of the effects of heat-treatment conditions and design parameters on the mechanical properties of TPMS structures.

5.0 Conclusion:

In summary, the uniaxial tensile testing of composite TPMS structures, with and without heat treatment, has revealed important insights. The as-printed sample exhibited moderate ductility. Notably, all three heat-treated samples, regardless of the specific heat treatment conditions (temperature and duration), displayed improved ductility at the expense of strength. It is noteworthy that as heat treatment duration increased, strength decreased. Of particular interest was the observation of a sample subjected to 80°C heat treatment for 2 hours. This sample exhibited a balance between moderate ductility and strength. Notably, this specific heat-treatment condition increased failure strain by 44.3% compared to the as-printed sample and played a crucial role in enhancing fracture toughness. Another intriguing finding is that heat treatment duration had a minimal impact on ductility enhancement but significantly reduced UTS. Additionally, the presence of TPU infill in the void space was found to significantly impact fracture behavior. Ongoing research plans aim to delve deeper into the effects of heat-treatment conditions and design parameters on the mechanical properties of TPMS structures. These findings open up promising avenues for further exploration and development in this field.

6.0 Key Advancement and Future Prospects:

6.1 Key Advancement: We have chosen bio-friendly and sustainable filaments made of PLA alongside TPU. These biodegradable PLA polymers can be explored for lattice fabrication, making additive manufacturing more eco-friendly. Bioinspired lattice structures often exhibit intricate geometries found in nature, (as depicted in Fig. 1). In this project, we have successfully optimized process parameters for FFF printing of composite TPMS structures to achieve complex geometries, enhancing strength and ductility as well as material utilization. In recent years, the utilization of multiple materials in Fused Filament Fabrication (FFF) has broadened the horizons for lattice construction. As a result, we chose the path of Dual-extrusion FFF printing to craft these composite structures, harnessing the advantages of various materials to attain enhanced properties

6.2 Future Prospects: Bioinspired lattice components hold great promise in the biomedical and sports gear field. Customized bone scaffolds, and implantable devices as well as football helmets designed to match the patient's/athlete's anatomy are being explored. Moreover, FFF has the potential to contribute to sustainability goals. Future NSF funding will continue to drive research into sustainable materials, recycling, and reducing waste in the FFF process. NSF can foster collaborations between materials science, manufacturing engineering, and biology to accelerate the development of innovative bioinspired lattice components. This interdisciplinary approach can lead to breakthroughs in various fields.

7.0 Summary:

The NSF has played a critical role in advancing the field of advanced manufacturing. Advanced Manufacturing technology has the potential to revolutionize industries ranging from aerospace to medical, all while contributing to a more sustainable future. Continued funding and support from the NSF will be vital in realizing the full potential of this promising area of research.

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